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(54) **Electronic aircraft braking system with brake wear measurement, running clearance adjustment and plural electric motor-actuator ram assemblies**

(57) An electrically actuated aircraft brake system (20) and method which provides for brake wear measurement, brake running clearance adjustment, ram position-based control and improved construction and operation. Brake wear and running clearance measurement are obtained by analyzing the output of position sensing circuitry. The position sensing circuitry, preferably including a LVDT position sensor (36, 74, 174), is also used to determine braking load, a brake controller (21) including circuitry for effecting displacement of one or more reciprocating rams (35) to load a brake disk stack (80) by a predetermined amount based on a present displacement value of the position signal obtained from the position sensor (36, 74, 174). The position sensor (36, 74, 174) preferably includes a LVTD transducer connected between the reciprocating ram (35) and a brake housing (47), and the motive device preferably includes a servo motor (33, 150). Also provided is an actuator housing (147) including a guideway (165) for each ram (35), the guideway (165) and ram (35) having the same polygonal cross section, whereby the ram nut (163) is guided and restrained from rotation by the guideway (165) as it is translated by a ball screw (162) in threaded engagement with the ram nut (163) for selective movement into and out of forceful engagement with the brake disk stack (80) for allying and releasing braking force on a rotatable wheel. The electric servo motor (33, 150) is drivingly connected to each ball screw (162) by a first gear (159) integral with the ball screw (162), a second gear (156) is mesh with the first gear (159), and a pinion (157) on a rotating drive shaft (158) of the electric motor (150).

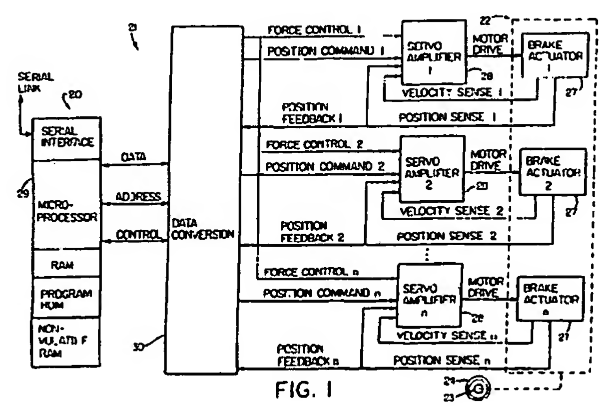

FIG. 1

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[0011] The aircraft brake system of the present invention is defined by claim 1 and the method is defined by claim 13.

[0012] The present invention provides a brake system and method, particularly an electrically actuated aircraft brake system and method, which provides various advantages over known brake systems and methods.

[0013] According to one aspect of the invention, a brake system and method are provided to enable brake wear measurement while eliminating the need for previously used brake wear indicator pins.

[0014] Accordingly, a preferred embodiment of the invention provides a brake system and method characterized by a brake disk stack, at least one reciprocating ram, a motive device operatively connected to the reciprocating ram for selectively moving the reciprocating ram into and out of forceful engagement with the brake disk stack for applying and releasing braking torque on a rotatable member (e.g., a wheel), and a controller that controls the motive device for selective control of the reciprocating ram and regulation of the force applied by the reciprocating ram against the brake disk stack. In accordance with the invention, a position sensor supplies a position signal representative of the position of the reciprocating ram, and the controller includes means for effecting displacement of the reciprocating ram to load the brake disk stack by a predetermined amount to obtain from the position sensor a present displacement value of the position signal, and for comparing the present displacement value to a reference displacement value to provide a measurement of wear of the brake disk stack.

[0015] A preferred embodiment of the invention is further characterized by the use of a position sensor directly linked to the actuator ram, and preferably one that is robust. A preferred position sensor is a LVDT transducer, although other types of transducers may be used, for example a potentiometer, an optical encoder, a RVDT transducer with a rotary input provided by suitable gearing, etc. As is preferred, the LVDT transducer is connected between the reciprocating ram and a brake housing to which the motive device is mounted. The motive device preferably is an electric servo motor, and the controller preferably includes a processor for controlling actuator position and application force. The processor preferably is programmed to perform the aforesaid brake wear measurement, and also a new brake disk stack measurement routine for obtaining a brake wear reference value for the new brake disk stack. The new brake disk stack measurement routine includes the steps of effecting displacement of the reciprocating ram to load the new brake disk stack by a predetermined amount to obtain from the position transducer a new brake disk stack displacement value of the position signal and then storing, preferably in non-volatile memory, the new brake disk stack displacement value as the reference displacement value against which subsequently obtained present displacement values are compared to provide a measurement of wear of the brake disk stack.

[0016] The present invention also provides a brake system and method, particularly an electrically actuated aircraft brake system and method, which provides for running clearance adjustment while eliminating the need for previously used mechanical adjustor devices. Running clearance adjustment is obtained by performing a running clearance adjustment routine which analyzes the output of the position sensing circuitry. In a preferred embodiment, the brake controller is operable to effect movement of the reciprocating ram for loading the brake disk stack by a predetermined amount to obtain from the position transducer a present displacement value of the position signal, and then to use the present displacement value to determine a running clearance position of the reciprocating ram. More particularly, provision is made for subtracting the predetermined clearance value from the present displacement value to obtain a new running clearance value, storing the new running clearance value in memory, and then using the new running clearance value in determining the running clearance position of the reciprocating ram.

[0017] As will be appreciated, an improved brake system arises from the use of the above summarized wear measurement and running clearance features. In addition, these features are particularly useful in aircraft brake systems and particularly an electrically actuated aircraft brake system which does not need hydraulic components which are subject to various drawbacks including fluid leaks, high maintenance requirements, fire hazard, higher overall weight, etc.

[0018] The foregoing and other features of the invention are hereinafter fully described and particularly pointed out in the claims, the following description and the annexed drawings setting forth in detail one or more illustrative embodiments of the invention, such being indicative, however, of but one or a few of the various ways in which the principles of the invention may be employed.

BRIEF DESCRIPTION OF THE DRAWINGS

[0019]

Fig. 1 is a diagrammatic illustration of an exemplary multi-actuator computer-controlled brake actuation system.

Fig. 2 is a diagrammatic illustration of a brake actuator and associated servo amplifier employed in the system of Fig. 1.

Fig. 3 is a perspective view of an exemplary brake housing and actuator assembly useful in the system of Fig. 1.

Fig. 4 is a schematic view showing a brake actuator assembly in relation to a new brake disk stack.

Fig. 5 is a schematic view showing the brake actuator in relation to a worn brake disk stack.

Fig. 6 is a flowchart illustrating a method for meas-

erating the analog position commands and the analog motor current control commands to the four actuators, analog-to-digital data conversion to monitor the actuator position sense and motor current feedback signals, and signal discretes for auxiliary functions such as motor brake control. The micro-processor may also be interfaced via a serial communication link with other control components as needed, such as, for example, a anti-skid brake control unit. Although a micro-processor is utilized in the illustrated preferred embodiment, processing alternatively could be done analog as opposed to digital, or intermixed with digital processing as may be desired.

[0026] In the illustrated system, the four servo amplifiers 28 (Fig. 2) are independent and functionally identical, each amplifier being controlled by the micro-processor 29, responding to the position commands and motor current control signals from the processor, and feeding back the actuator position and motor current sense signals to the processor via the I/O circuitry 30.

[0027] The controller may use two separate power sources: for example, a 28 VDC supply to power the low level electronic circuitry and 28 to 270 VDC supply to power the four actuator motors through the motor driver power stage. The 28 VDC actuator power may be utilized in emergency situations when 270 VDC is not available to power system fault.

[0028] Further details of an exemplary brake actuator assembly 22 are shown in Figs. 3 -5. The brake actuator assembly includes a housing 47 that provides for the mounting of an electro-mechanical actuator 27, it being understood that typically multiple actuators will be mounted to the housing, such as four functionally identical actuators located at respective quadrants of the housing. The illustrated housing has a bolt circle 48 for mounting to the overall wheel and brake assembly 23 (Fig. 1). Each actuator 27 may include a DC brushless servo motor 50 and suitable reduction gearing 52 that translates rotary motor motion to linear motion of the ram 35 (the rams are hidden from view in Fig. 3). The brushless DC servo motor 50 may have integrated or otherwise associated therewith a friction type, fail-safe (power-off engaged) brake (not separately shown), and a resolver (not separately shown) for motor rotor commutation and angular velocity sensing. The resolver provides motor position feedback and velocity information. In particular, the resolver provides an electrical signal that is proportional to motor shaft position.

[0029] The ram 35 of each actuator is mechanically connected to an LVDT position sensor 74, such as by bracket 75. The LVDT armature 76 may be adjustably attached to the bracket (or the sensor body to the brake housing) by suitable means that provides for LVDT setting and position calibration. A cover (not shown), or the like, may be provided to protect for the LVDT mounting mechanism. Although an LVDT sensor is preferred, other types of position sensors/transducers may be used as desired for a particular application.

[0030] The purpose of the brake actuator(s) 27 is to impress a clamping force on the stack 80 of brake disk elements. The electro-mechanical (EM) actuator(s) operate simultaneously to produce a clamping force between a brake reaction plate 78 and the actuator output rams 35. An exemplary system utilizes four actuators, operating simultaneously, to provide the total brake clamping force required. However, the size and number of actuators may be varied to provide the total brake clamping force required. The actuators may be operated in a controlled displacement mode such that the clamping force is proportional to the deflection of the reaction plate. Although each actuator can operate independently, the actuators may be commanded in pairs (or otherwise), the actuators of each pair being located physically on diametrically opposite sides on the brake housing.

[0031] The brake disk stack 80 includes alternating rotor disks 81 and stator disks 82 mounted with respect to a torque tube 83 or similar member and the wheel (not shown) for relative axial movement. Each rotor disk 81 is coupled to the wheel for rotation therewith and each stator disk 82 is coupled to the torque tube 83 against rotation. A back plate 85 is located at the rear end of the brake disk stack and functions as a force reaction member via the reaction plate 78. The brake actuator 27 is mounted to brake housing 47 fixed with respect to the torque tube. The ram 35 of the actuator extends to compress the brake disk stack 80 against the back plate 85, and torque is taken out by the stator disks 82 through the static torque tube 83 (or the like).

[0032] As the brake disks wear, the collective axial thickness thereof will decrease. In accordance with the invention, the controller 21 (Fig. 1) is suitably programmed to carry out a wear measurement routine which is illustrated by the flow chart shown in Fig. 6 and a running clearance adjustment routine which is illustrated by the flow chart shown in Fig. 9. The wear measurement routine preferably uses a reference value corresponding to zero wear, such value corresponding to the thickness of a new brake disk stack. The new brake stack reference value is determined by the controller in accordance with a routine illustrated by the flow chart shown in Fig. 7. Both the wear measurement routine and the new brake disk stack reference measurement routine preferably use a further routine for measuring actuator displacement, this routine being illustrated by the flow chart shown in Fig. 8.

[0033] In Fig. 8, actuator displacement measurement begins at step 88 where the actuator rams (or ram in a single actuator system) are extended by the controller to load the brake disk stack by a predetermined amount. The amount of loading need only be enough to ensure that the individual disks of the brake disk stack are held against one another to remove any slack in the stack. For this purpose, the actuator rams preferably apply about 10% of maximum braking force to the brake disk stack. At step 89, the displacement (travel) X of each actuator ram is measured using the respective position

rams can all be extended to engage the brakes and then the motor brakes may be engaged to hold the actuator rams in their extended/engaged positions. Once the motor brakes are engaged, power to the motor components of the servo motor 150 (the ram drive motor components) can be shut off. The specific motor selection will be dependent on the requirements for a given braking application. In the illustrated embodiment, the servo motor components, friction brake and resolver are all integrated into a common motor housing and collectively may be referred to as a servo motor.

[0039] As shown in Figs. 12-15, the intermediate cluster gear member 151 provides for two stages of reduction gearing and includes a first stage gear 155 and a second stage gear 156. The first stage gear, which provides the first stage of gear reduction, is a bevel gear that meshes with a bevel gear 157 integral with the drive shaft 158 of the motor. The second stage gear 156 is a straight spur gear that mates with a ball screw gear 159 formed integrally with a ball screw 162. The intermediate cluster gear member is supported by ball bearings 160 and 161 at its ends. Although reference herein is made to certain structures as being integral as is preferred, it should be understood such structures alternatively may be composed of discrete components joined together to form a functionally equivalent structure.

[0040] The ball screw assembly 152 is comprised of the ball screw 162 with the integral gear 159, a hexagonal ball nut 163 that translates rotary motion to linear motion of the ball nut, and a pad 164 that attaches to the end of the ball nut and provides the interface to the brake disk pressure plate. The ball screw and ball nut, which provide a third stage of reduction, may be of a known configuration and thus the respective spiral grooves thereof and associated balls have not been illustrated as the same would be immediately evident to one skilled in the art. The ball nut (also herein referred to as a ram or ram nut) is free to translate along the axis of the ball screw upon rotation of the ball screw, but not to rotate, as the ball nut is guided by a hexagonal bore 165 in the housing 147.

[0041] As best seen in Fig. 16, the hexagonal bore or guideway 165 and the ball nut 163 respectively have, in the illustrated preferred embodiment, corresponding polygonal cross-sections defined by plural inner/outer side surfaces (commonly indicated by reference numeral 166) which rotationally interfere with one another to restrain rotation of the ram nut 163 relative to the housing 147. As is preferred and illustrated, one or more of the side surfaces, most preferably all of the side surfaces, are planar and form regular polyhedrons providing a close sliding fit between the ball nut and guideway. It will be appreciated, however, that other configurations may be used although less preferred. For example, the number of sides may be varied from the illustrated six-sided polygons (hexagons), as may be desired for a particular application. The six-sided polyhedral configuration provides desired sliding and antirotational characteristics.

[0042] Preferably, a lubricant, particularly a suitable grease, is used to lubricate that relatively sliding surfaces 166 of the ball nut 163 and guideway 165. It has been found that the grease and close clearance between the ball nut and guideway prevent entry of any appreciable amount of dirt or other foreign material at the sliding surfaces interface so as to prevent any significant degradation of performance. However, if desired, a suitable seal, such as a wiper seal or a rolling diaphragm seal, could be employed to seal against passage of dirt or other undesirable materials between the sliding surfaces. An exemplary grease for the ball screw and ram nut assembly is MIL-G-81322 and an exemplary grease for the gear train is MIL-G-81827.

[0043] The driving torque is applied to the mechanism through the integral gear 159 that drives the ball screw 162 causing the ball nut 163 to translate thus converting input torque to linear output force. The translating ball nut contacts the front of the stack of brake disks through the interface pad 164 and functions as an actuator ram 135. The ballscrew is supported by three bearings, a radial bearing 167 and a thrust roller bearing 168 at the outboard end of the ball screw and a radial ball bearing 169 at a location intermediate the nut-engaging threaded portion of the ball screw and the integral gear 158. A bearing plate 170 is used to support the ball bearing 169 in the housing. An actuator cover 171 locates the radial and thrust bearings and provides mechanical thrust support for the ball screw. The cover is attached to the actuator housing by suitable means such as screws 172 (Fig. 11).

[0044] Each ball nut 163 (actuator ram 135) is mechanically connected to an LVDT position sensor 174, such as by bracket 175. The LVDT armature 176 may be adjustably attached to the bracket (or the sensor body to the brake housing) by suitable means that provides for LVDT setting and position calibration. A cover 177 may be provided to protect the LVDT mounting mechanism. Although an LVDT sensor is preferred, other types of position sensors/transducers may be used as desired for a particular application.

[0045] Like the brake actuators 27 (Figs. 4 and 5), the purpose of the brake actuator(s) 127 is to impress a clamping force on a stack of brake disk elements. The electro-mechanical (EM) actuator(s) operate simultaneously to produce a clamping force between a brake reaction plate and the actuator output rams 135. Again, the size and number of actuators may be varied to provide the total brake clamping force required. The position of the rams, as opposed to motor current, preferably is used to obtain desired braking load. It is noted however that the above described running calibration technique is carried out in a current mode, although with use of the position transducer.

[0046] The use of position sensing and position servo for controlling brake force application provides advantages over other control methodologies. One advantage

bracket are rotationally interlocked.

[0053] The recess 190 is formed in the radially outer peripheral portion 189 of the housing 147 which is circumferentially continuous and circumscribes housing compartments containing the motors 150 and the guideways 165 containing the actuator ram nuts 163 as best seen in Figs. 1 and 17. At the side of the housing diametrically opposite the recess, there is provided another recess 193 for a load cell 194. As is preferred, the housing is formed slightly oblong at its end adjacent the load cell recess 193 so that additional housing structure protrudes radially outwardly of the circular peripheral portion thereof to provide a radially enlarged receptacle for the load cell. It is noted that this arrangement is enabled by the use of the above described intermediate cluster gear member 151. In addition to providing two stages of gear reduction, the intermediate cluster gear member 151 allows the motors to be positioned radially inwardly of the outer peripheral ring portion of the housing and thus provides radial clearance with the load sensor and the torque lug.

[0054] The load cell 194 is mounted to the torque take-out bracket at the end thereof diametrically opposite the end thereof including the torque reaction recess 187. Accordingly, the load cell functions as a secondary lug for torque take-out and thus the output of the load cell will be indicative of brake torque.

[0055] As though skilled in the art will appreciate, other types of screw drives may be used in place of the preferred ball screw drive. Accordingly, the reference herein to lead screw is intended to be a generic reference to screw drive devices and the like.

[0056] The various functions performed by the above described integers (components, assemblies, devices, compositions, etc.), the terms (including a reference to a "means") used to describe such integers are intended to correspond, unless otherwise indicated, to any integer which performs the specified function of the described integer (i.e., that is functionally equivalent), even though not structurally equivalent to the disclosed structure which performs the function in the herein illustrated exemplary embodiment or embodiments of the invention. In addition, while a particular feature may have been described above with respect to only one of several illustrated embodiments, such feature may be combined with one or more other features of the other embodiments, as may be desired and advantageous for any given or particular application.

Claims

1. A brake system comprising:

   a brake disk stack;
   a reciprocating ram;
   a motive device operatively connected to the reciprocating ram for selectively moving the reciprocating ram into and out of forceful engagement with the brake disk stack for applying and releasing braking force on a rotatable wheel;
   a controller for controlling the motive device for selective control of the reciprocating ram and regulation of the force applied by the reciprocating ram against the brake disk stack, and
   a position sensor which supplies a position signal representative of the position of the reciprocating ram; and

   wherein the controller includes means for effecting displacement of the reciprocating ram to load the brake disk stack by a predetermined amount based on a present displacement value of the position signal obtained from the position sensor.

2. A brake system as set forth in claim 1, wherein the position sensor includes a LVDT transducer.

3. A brake system as set forth in claim 2, comprising a brake housing to which said motive device is mounted, and said LVDT transducer is connected between said reciprocating ram and brake housing.

4. A brake system as set forth in any preceding claim, wherein the motive device is a servo motor.

5. A brake system as set forth in any preceding claim, in combination with an aircraft wheel assembly.

6. A brake system as set forth in any one of claims 1-5, wherein the controller includes means for effecting movement of the reciprocating ram for loading the brake disk stack by a predetermined amount to obtain from the position sensor a present displacement value of the position signal, and then using said present displacement value to determine a running clearance position of the reciprocating ram.

7. A brake system as set forth in claim 6, wherein said using step of said running clearance adjustment routine includes the steps of subtracting a predetermined clearance value from said present displacement value to obtain a new running clearance value, storing the new running clearance value in memory, and then using the new running clearance value in determining the running clearance position of the reciprocating rams.

8. A brake system as set forth in any preceding claim, comprising a plurality of actuator assemblies circumferentially spaced around a center axis of the brake disk stack.

9. A method for controlling operation of a brake system, the brake system including a motive device op-

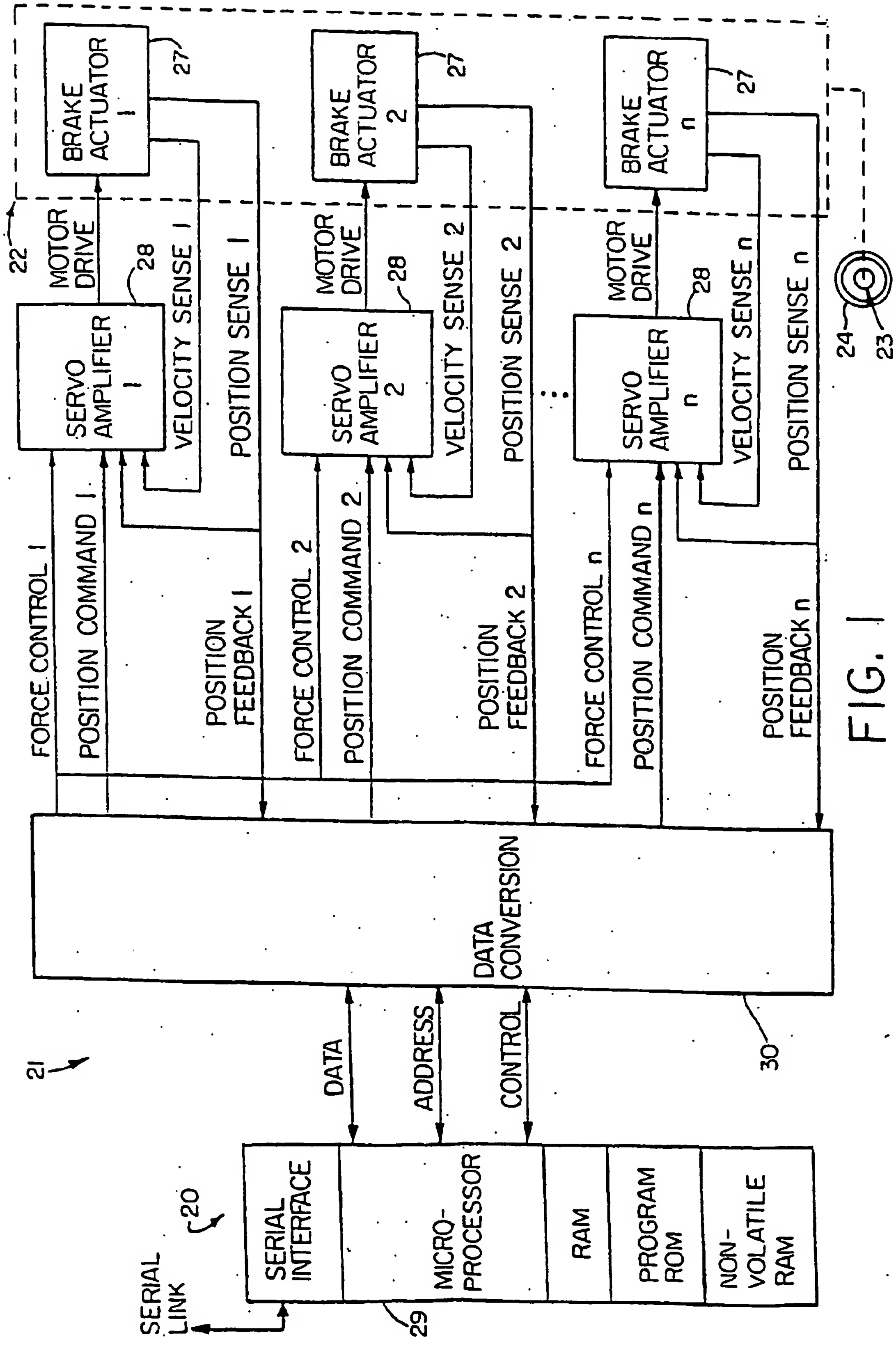
BRAKE ACTUATOR 1
BRAKE ACTUATOR 2
BRAKE ACTUATOR n
27
22
MOTOR DRIVE
28
SERVO AMPLIFIER 1
SERVO AMPLIFIER 2
SERVO AMPLIFIER n
VELOCITY SENSE 1
VELOCITY SENSE 2
VELOCITY SENSE n
POSITION SENSE 1
POSITION SENSE 2
POSITION SENSE n
24
23
FORCE CONTROL 1
POSITION COMMAND 1
POSITION FEEDBACK 1
FORCE CONTROL 2
POSITION COMMAND 2
POSITION FEEDBACK 2
FORCE CONTROL n
POSITION COMMAND n
POSITION FEEDBACK n
DATA CONVERSION
30
21
DATA
ADDRESS
CONTROL
20
SERIAL LINK
SERIAL INTERFACE
MICRO-PROCESSOR
RAM
PROGRAM ROM
NON-VOLATILE RAM
29

FIG. 1

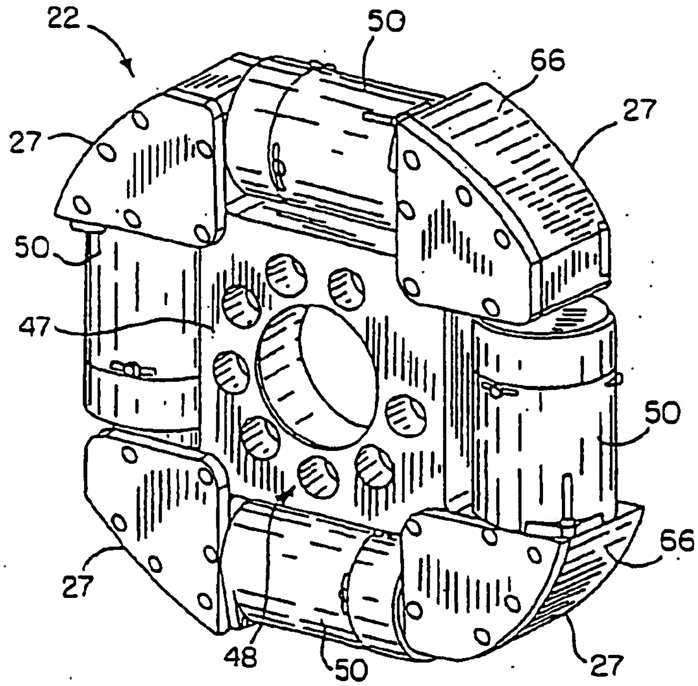

FIG. 3

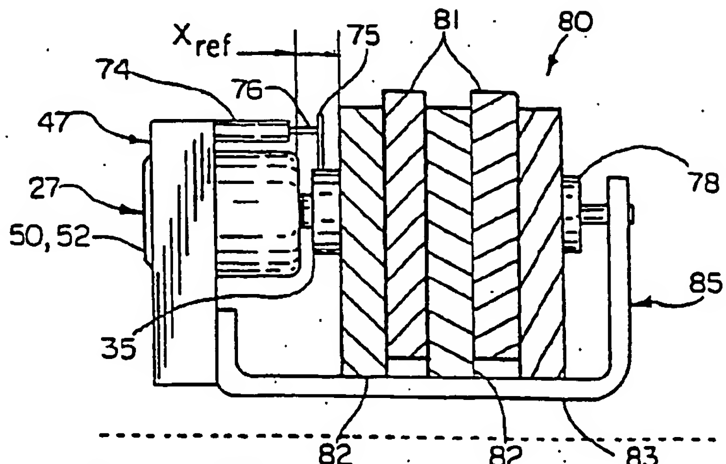

FIG. 4

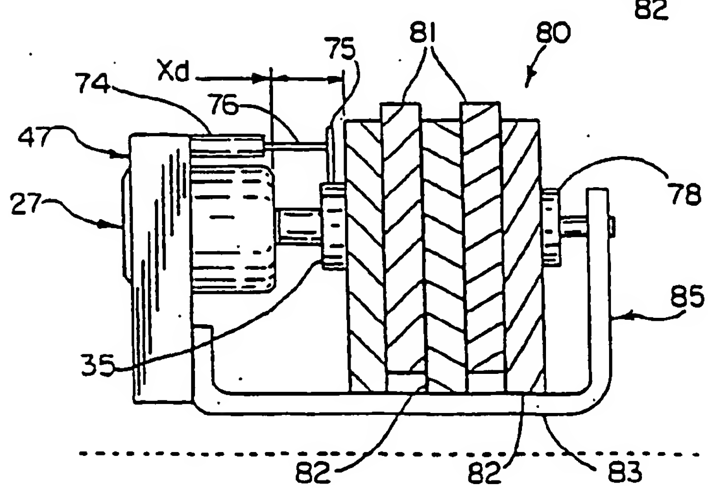

FIG. 5

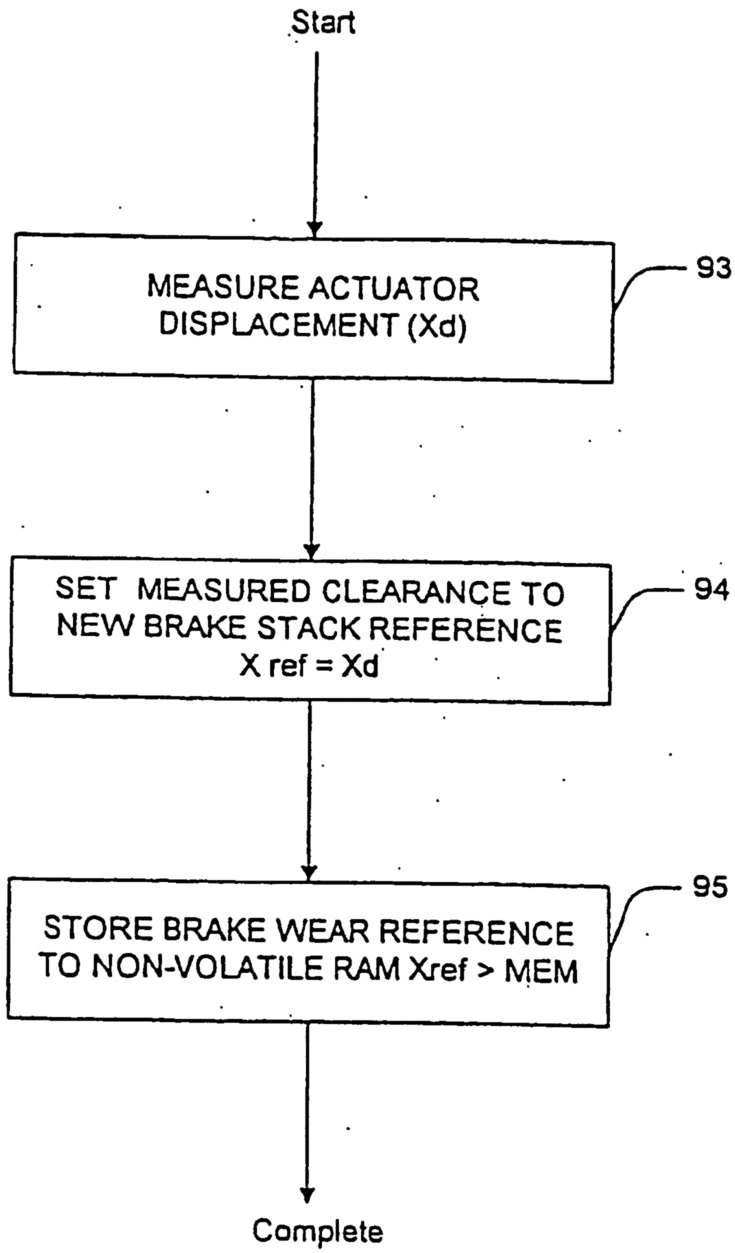
Start
MEASURE ACTUATOR DISPLACEMENT (Xd)
93
SET MEASURED CLEARANCE TO NEW BRAKE STACK REFERENCE X ref = Xd
94
STORE BRAKE WEAR REFERENCE TO NON-VOLATILE RAM Xref > MEM
95
Complete

FIG. 7

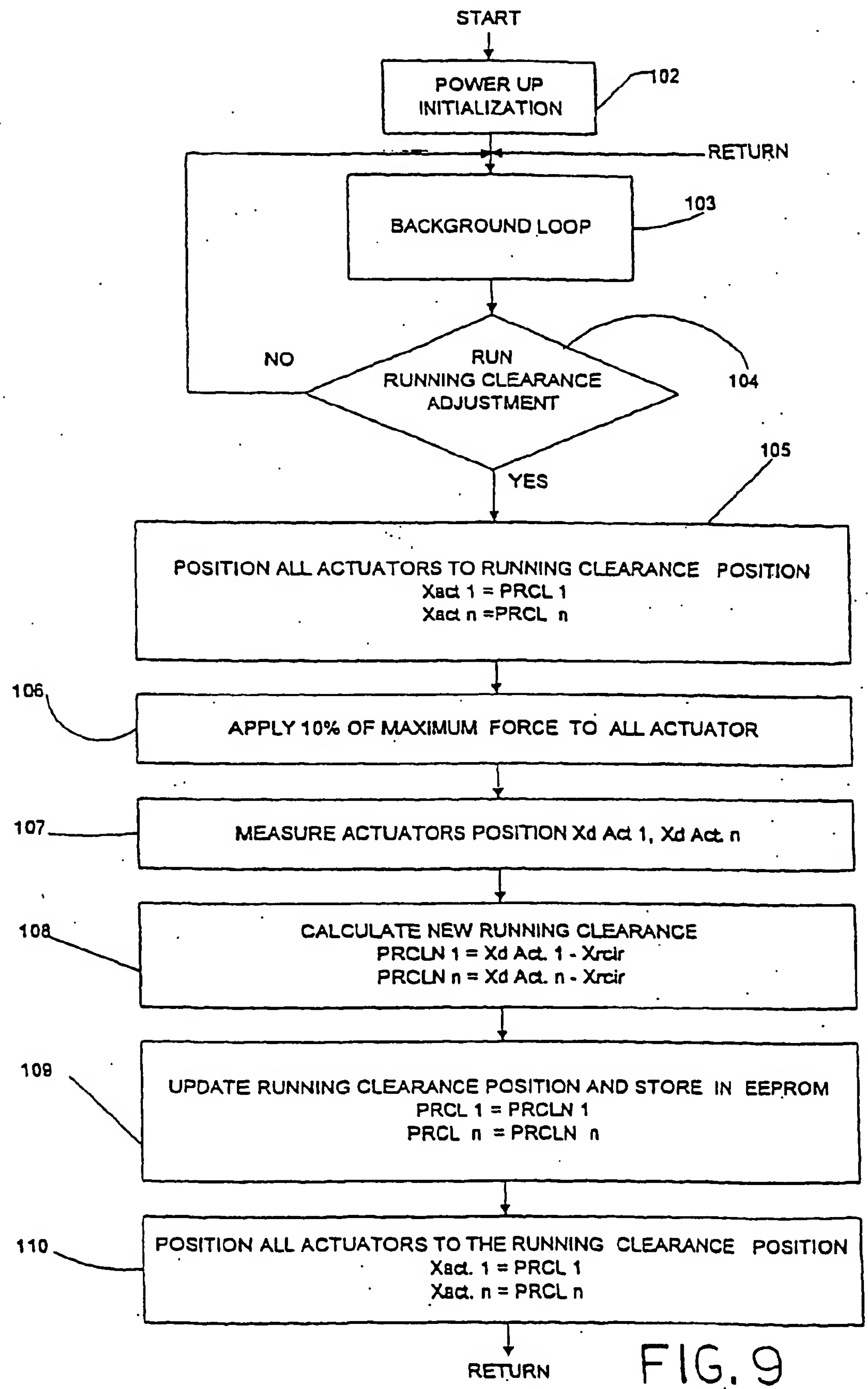
START
POWER UP INITIALIZATION
102
RETURN
BACKGROUND LOOP
103
RUN RUNNING CLEARANCE ADJUSTMENT
104
NO
YES
105
POSITION ALL ACTUATORS TO RUNNING CLEARANCE POSITION
Xact 1 = PRCL 1
Xact n =PRCL n
106
APPLY 10% OF MAXIMUM FORCE TO ALL ACTUATOR
107
MEASURE ACTUATORS POSITION Xd Act 1, Xd Act. n
108
CALCULATE NEW RUNNING CLEARANCE
PRCLN 1 = Xd Act. 1 - Xrclr
PRCLN n = Xd Act. n - Xrclr
109
UPDATE RUNNING CLEARANCE POSITION AND STORE IN EEPROM
PRCL 1 = PRCLN 1
PRCL n = PRCLN n
110
POSITION ALL ACTUATORS TO THE RUNNING CLEARANCE POSITION
Xact. 1 = PRCL 1
Xact. n = PRCL n
RETURN

FIG. 9

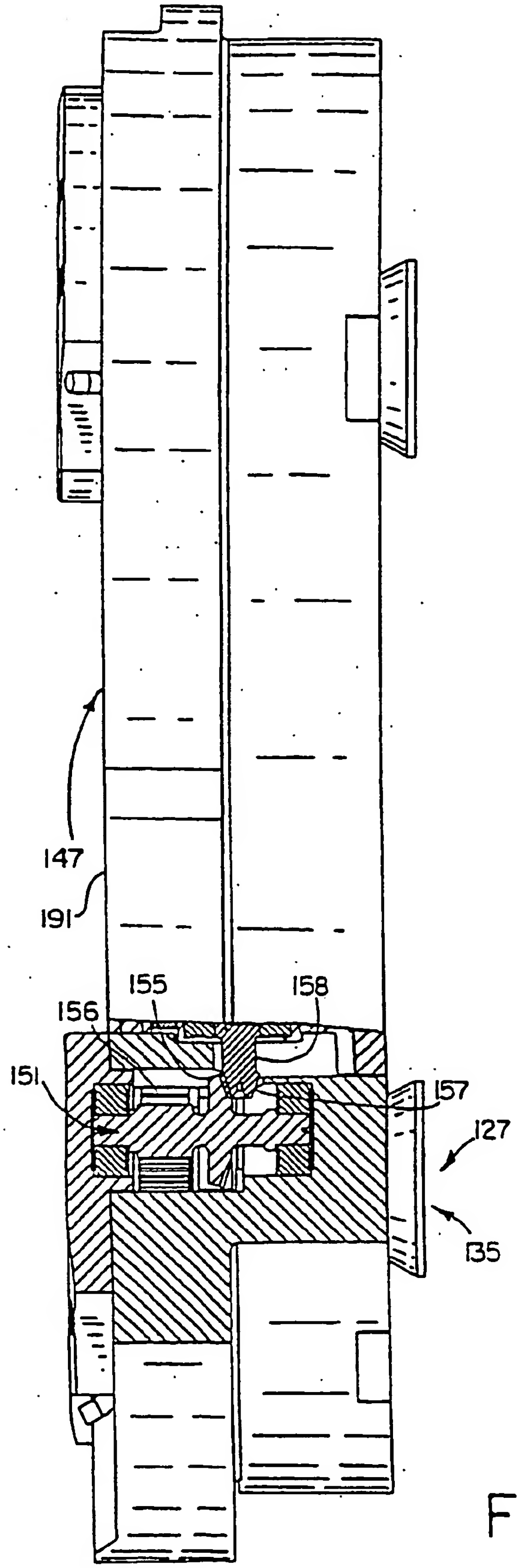

FIG. 12

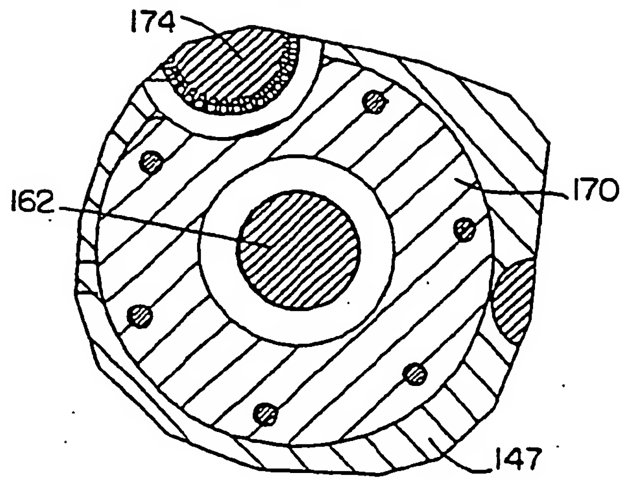

FIG. 15

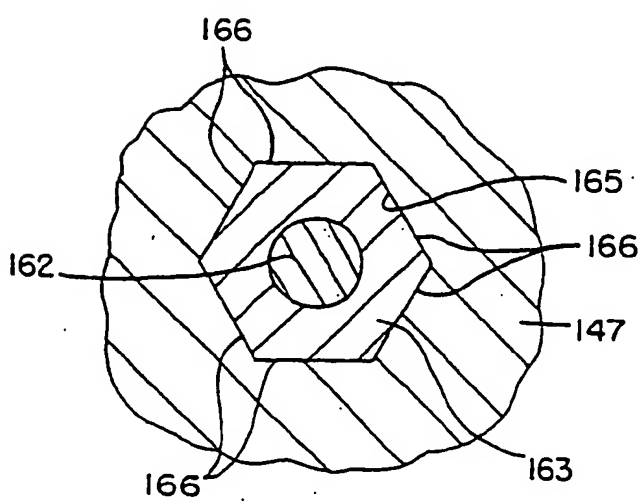

FIG. 16